Source Characteristics of Earthquakes Occurring in the Vicinity of Kyoto

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Abstract

Low magnification seismograms recorded at Abuyama Seismological Observatory are Fourier analyzed for estimating and comparing the source parameters of earthquakes of magnitude of 4.5 or greater occurring in the vicinity of Kyoto. A comparison of spectral parameters by use of an $\Omega-f_c$ diagram illustrates a fairly striking contrast of source parameters between the northern and southern sources. Earthquakes with high aftershock activity are, in general, characterized by low stress drop compared with earthquakes with low aftershock activity. The northern sources have generally higher stress drops and smaller dimensions than the southern sources and Wachi earthquakes. A possible interpretation of the high stress drop in the northern part may be that higher effective stress is acting there. The regional variation of seismic wave attenuation reported in a previous paper[2] seems to support this interpretation.

1. Introduction

It has been made clear by Okano and others that[1),2),3)], in the seismically active zone in the vicinity of Kyoto, which is known by the name of Yodogawa Seismic Zone, the significant regional variations in seismic activities, aftershock activities and seismic wave attenuation exist between the northern and southern parts. Many earthquakes occurring in the southern part of the seismic zone are characterized by higher aftershock activities than earthquakes with sources in the northern part[1)]. Seismic wave attenuation in this seismic zone is, as a whole, small for seismic waves propagating in the direction of EW which coincides with the direction of the global tectonic force acting in the region concerned. Seismic attenuation in the northern part is, however, lower than that in the southern part[2)]. It is very interesting that the regions with high and low attenuation correspond to the regions with high and low aftershock activities.

As is discussed in § 2, regionality is frequent and obviously seen in frequency contents of seismograms, especially the Sassa type low magnification seismograms recorded at Abuyama Seismological Observatory. This paper investigates the source characteristics of the earthquakes recorded by the low magnification seismograph by examining seismograms, measuring their shear wave spectra and interpreting the observations in terms of source parameters based on Brune's model of dislocation[4),5)], and a simple scheme for representing seismic source parameters developed by Hanks and Thatcher[6)].

2. Low magnification seismograms

In the seismically active zone in the vicinity of Kyoto, fourteen earthquakes of magnitude of 4.5 or greater occurred since 1963. Nine of them were clearly recorded by the Sassa type low magnification horizontal seismograph installed at Abuyama Seismological Observatory. This paper discusses these nine earthquakes. The epicenters are plotted in Fig. 1. The epicentral locations, magnitudes and focal depths of these earthquakes are listed in Table I. The Sassa type low magnification seismograph has a free period of 6.0 sec with a magnification of about 15. The frequency response curve is shown in Fig. 2.

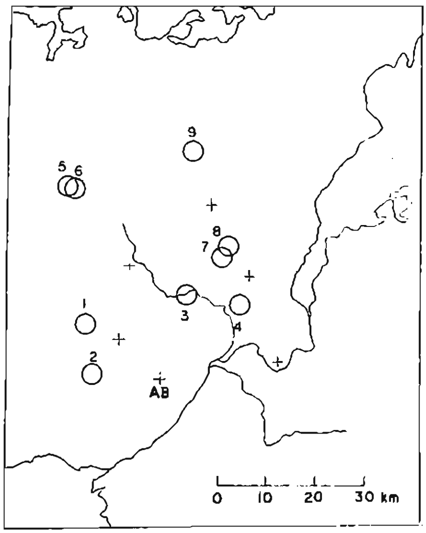

Fig. 1. Distribution of earthquakes examined in the present paper.

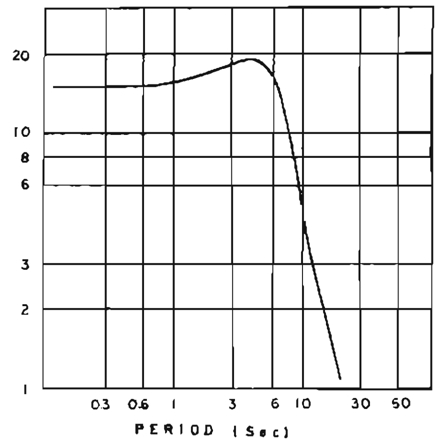

Fig. 2. Frequency response curve of Sassa type low magnification seismograph.

The low magnification seismograms of the nine earthquakes are reproduced in Figs. 3, 4 and 5. The two earthquakes shown in Fig. 3–a have nearly the same magnitude and occurred at comparable epicentral distance. As is easily seen, the first event has remarkable long period excitation, while the second one clearly demonstrates the unusual high frequency excitation of this source. The first event of magnitude of 5.6 which occurred at Wachi-cho in the northwest part of the seismic zone (No. 6) has a large number of aftershocks[7]. Aftershock activity has continued since the main shock occurred on Aug. 18, 1968. In contrast, the second event of magnitude of 5.4 occurring at Miyama-cho near the north end of the seismic zone (No. 9) is characterized by unusual low aftershock activity for an earthquake of this magnitude. Only fourteen aftershocks of magnitude of 1.5 or greater were observed within a month after the main shock occurred. Another pair of seismograms are reproduced in Fig. 3–b. The two earthquakes shown have the same magnitude (M4.5) and comparable epicentral distance. It is easily found that the frequency contents of the two seismograms are different from each other. The first event (No. 2) occurred in the south part of the seismic zone with a large number of aftershocks (more than 50). The second one with sources in the middle part (No. 4) are followed by a comparatively small number of aftershocks (less than 20). The earthquake No. 7

(M4.9) shown in Fig. 4 occurred in the north part. The aftershock activity is considerably low for an earthquakes of this magnitude[1]. The averaged frequency of this seismogram is apparently not so high as that of the earthquake with source near

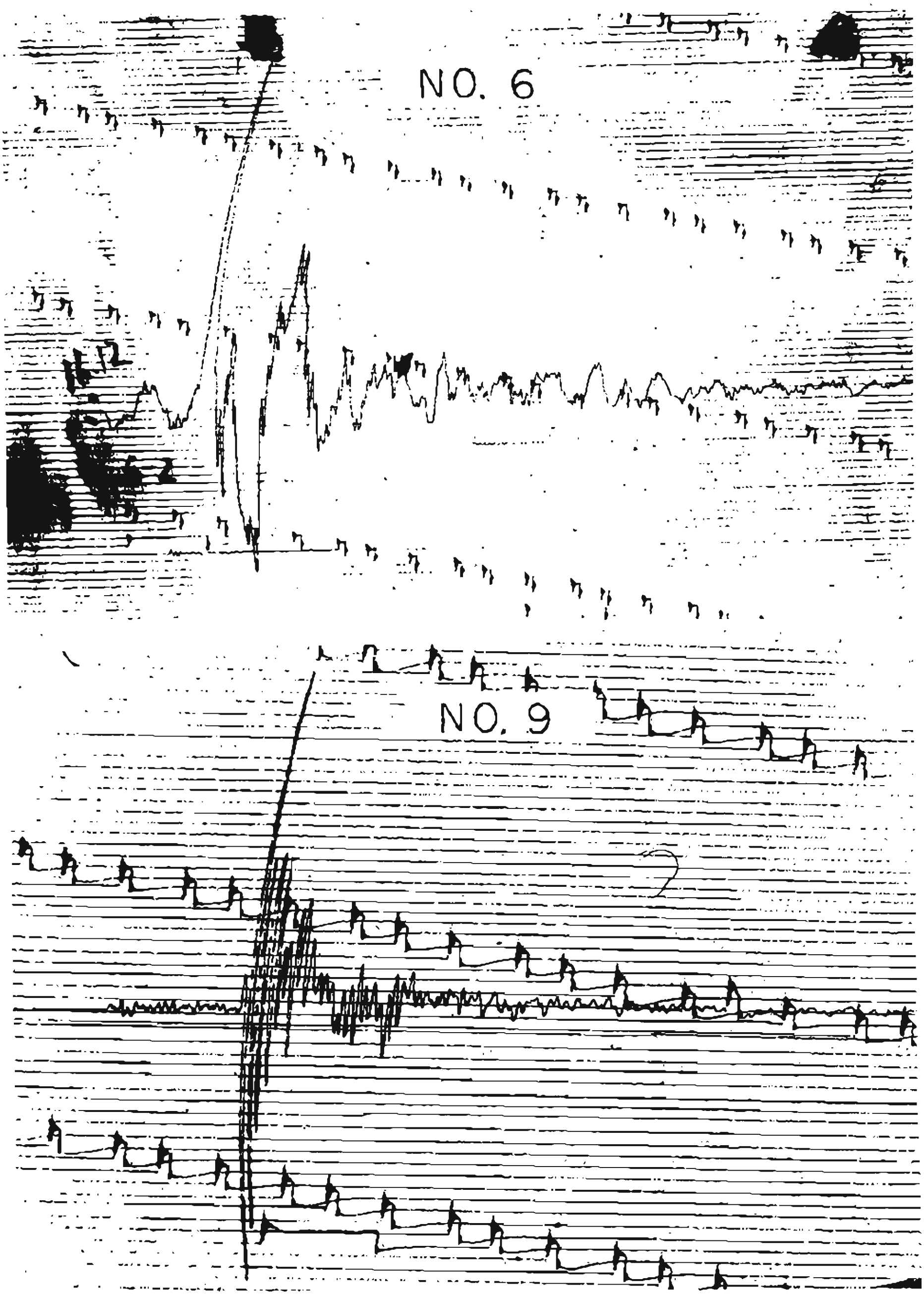

Fig. 3–a: Seismograms of earthquakes No. 6 and No. 9.

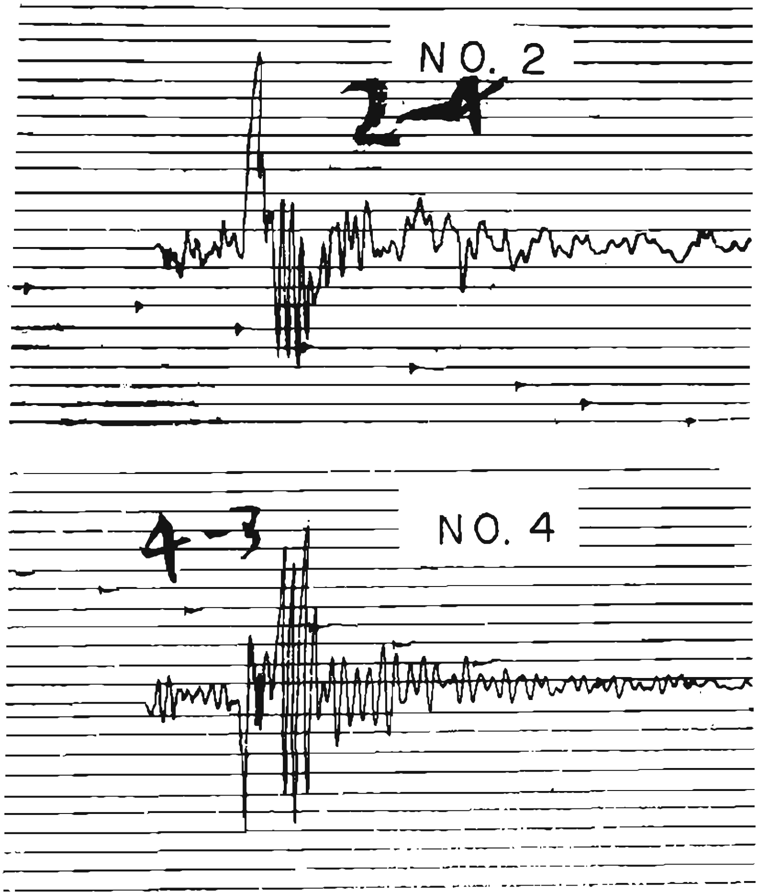

Fig. 3-b: Seismograms of earthquakes No. 2 and No. 4.

Fig. 3. Comparison of the low magnification seismograms.

the north end of the seismic zone (No. 9), but higher than that of the earthquakes in the southern part and Wachi-cho. The low magnification seismograms of the other earthquakes examined in this paper are reproduced in Fig. 5. Figs. 3, 4 and 5, with reference to Fig. 1, seem to demonstrate that the frequency contents of seismic

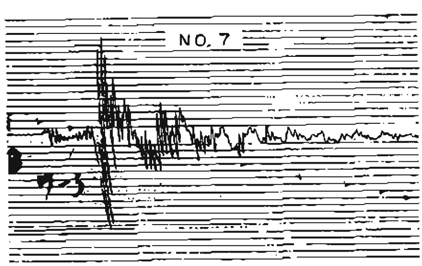

Fig. 4. Low magnification seismogram of earthquake No. 7.

Table 1. List of earthquakes examined in the present paper

Event No.	Date	Time h	Time m	Location	Magnitude	Depth
1	1966 June 15	17	30	W of Myoken	4.5	9
2	1966 June 29	21	22	W of Myoken	4.6	12
3	1967 June 21	21	10	W of Kyoto C.	4.5	9.5
4	1968 Jan. 20	11	31	E of Kyoto C.	4.7	7
5	1968 Feb 24	11	31	Wachi-cho	4.6	10
6	1968 Aug. 18	16	12	Wachi-cho	5.6	8
7	1968 Aug. 27	21	58	N of Kyoto C.	4.9	10
8	1968 Aug. 27	22	53	N of Kyoto C.	4.4	9
9	1972 Aug. 31	16	54	Miyama-cho	5.4	13

waves vary with regions. Indications are generally that seismograms of the earthquakes with sources in the southern part of the seismic zone and Wachi-cho region are characterized by lower frequency contents than those of earthquakes of similar magnitude with sources in the northern and middle part of the seismic zone. It is suggested that some correlation may exist between the frequency contents of seismic waves and the aftershock activity.

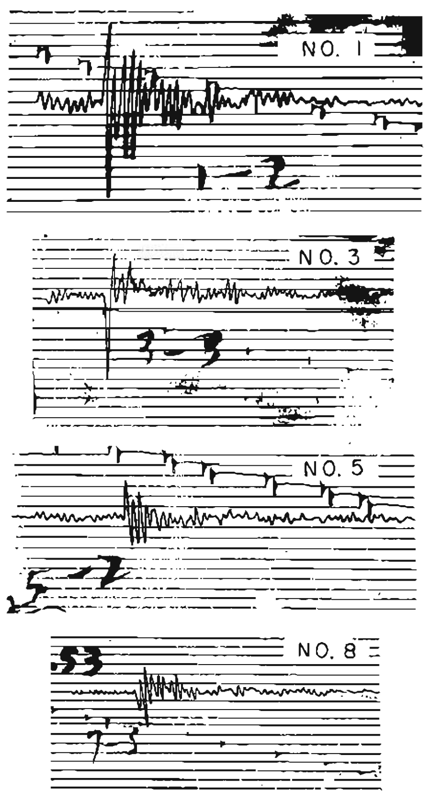

Fig. 5. Low magnification seismograms of earthquakes No. 1, No. 2, No. 5 and No. 8.

3. Shear wave spectra and comparison of source parameters

(3–1) Shear wave spectra

The seismograms shown in § 2 are fairly distorted with curvature and slight deflection of pen. The original seismograms must be, therefore, corrected for curvature and deflection for measuring spectra. The corrections were carried out analytically for every ten digitized values. The other digitized values were corrected by interpolation. Some of the corrected seismograms are shown in Fig. 6. The corrected seismograms are Fourier analyzed and corrected for instrument response, attenuation and geometrical spreading along path. Seismic wave attenuation in the seismic zone concerned has been discussed by Okano and Hirano[8]. The mean values of Q for shear wave was estimated to be greater than 300. In the present paper, two values of Q, 300 and 600, were used for correcting spectra. In the attenuation factor, the value of shear wave velocity β was taken as 3.5 km/sec, in agreement with the probable value for earthquakes in the seismic zone concerned[9]. Resulting spectra are shown in Fig. 7. In this figure, the shape of spectra does not appear to be particularly sensitive to the choice of Q within the range from 300 to 600.

Measured spectra shown in Fig. 7 were corrected for radiation pattern assuming possible nodal plane orientation and were reduced to as tandard distance of 20 km. The sampling lengths for use in the spectra analyses varied with each earthquake,

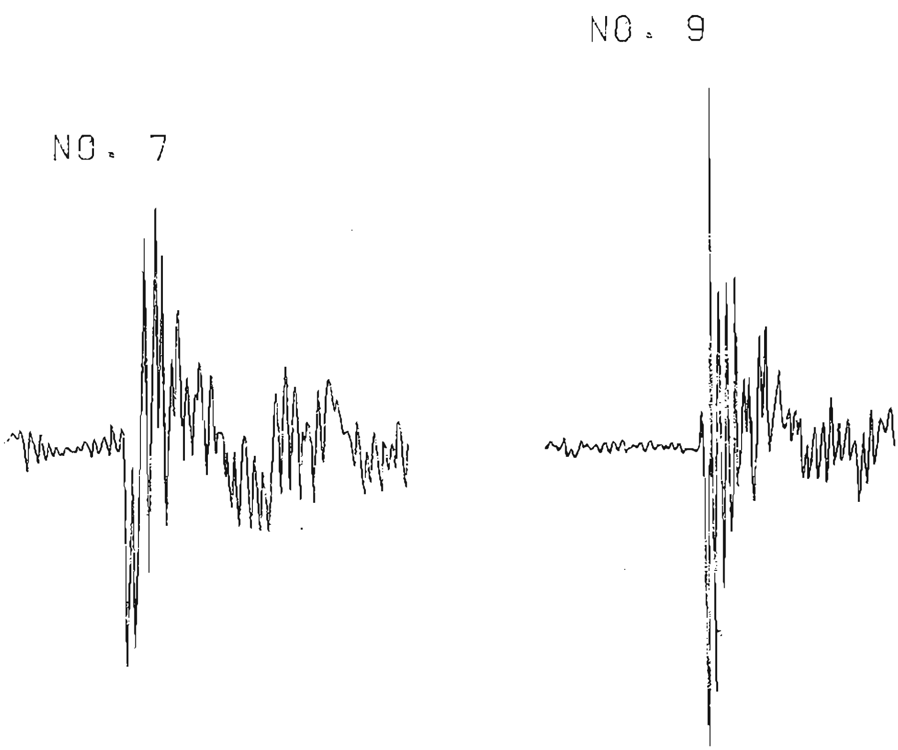

Fig. 6. Examples of the seismograms corrected for curvature and deflection.

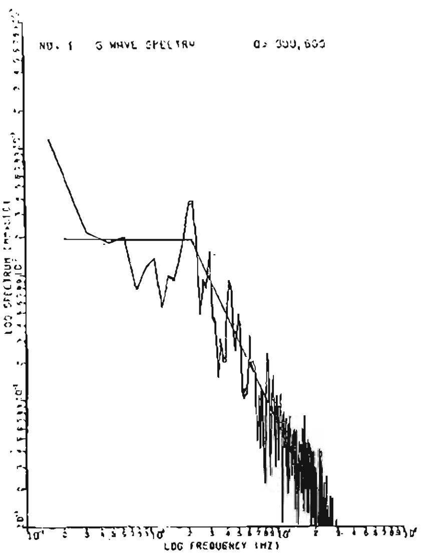

Fig. 7–1.

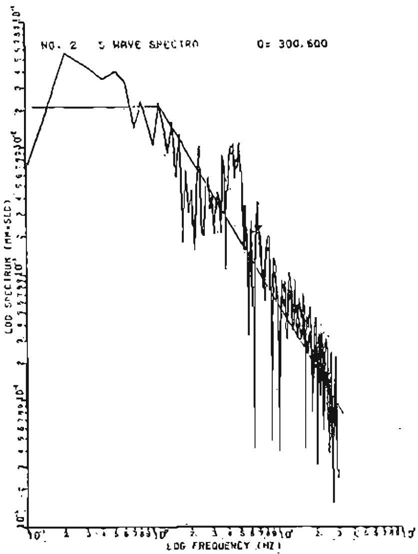

Fig. 7–2.

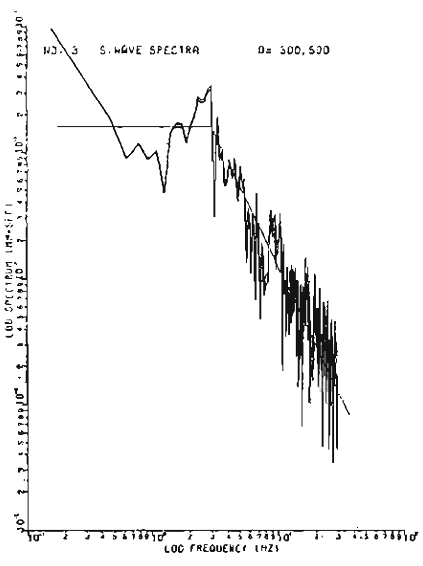

Fig. 7–3.

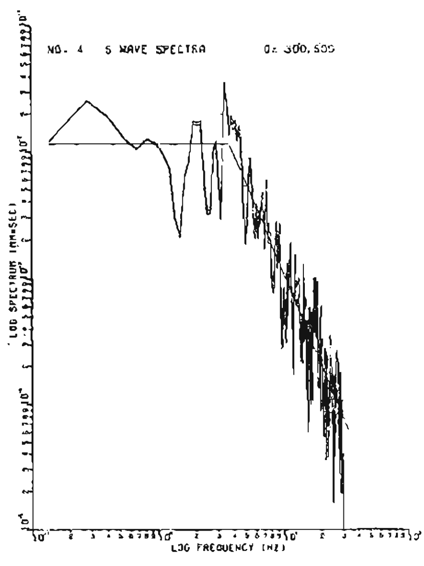

Fig. 7–4.

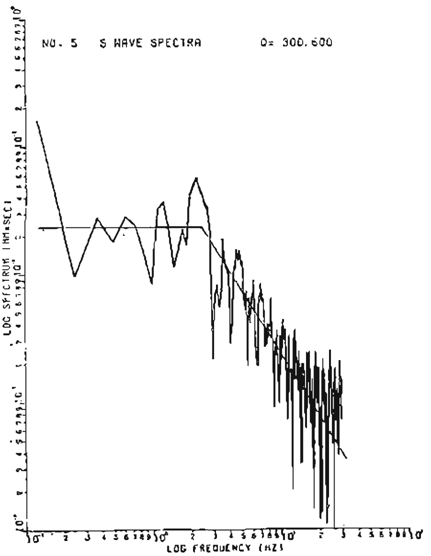

Fig. 7-5.

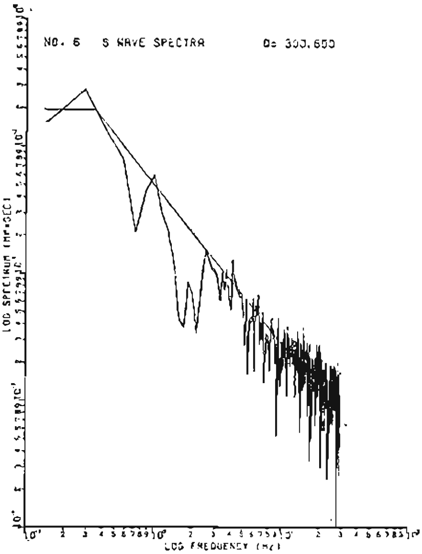

Fig. 7-6.

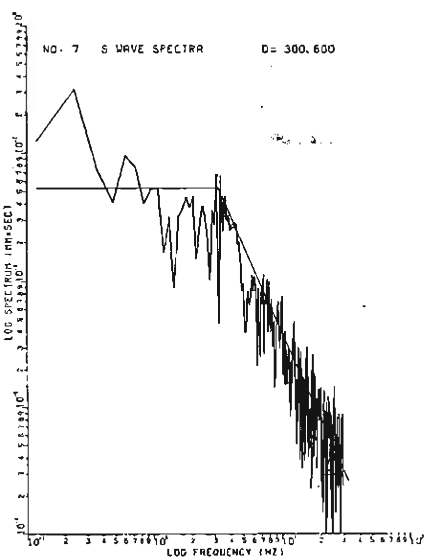

Fig. 7-7.

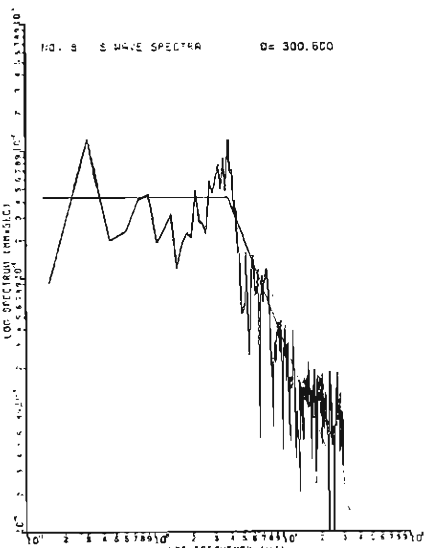

Fig. 7-8.

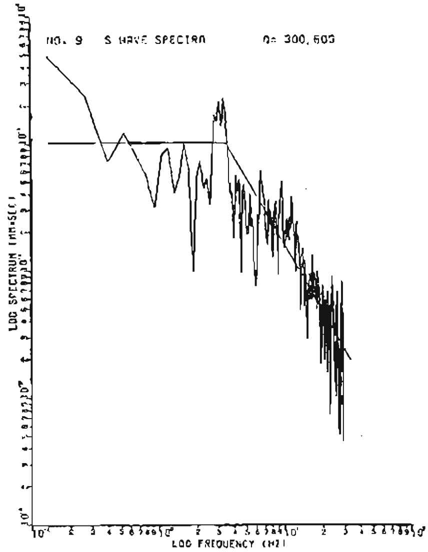

Fig. 7–9.

Fig. 7. Shear wave displacement spectra for the earthquakes listed in Table I. Effects of the choice of Q values (300 and 600) on the shape of spectra are also illustrated.

but they were taken to be sufficient duration for the purpose of the present study. A general characteristic of all the spectra can be considered as being similar to that of the displacement shear wave spectra expected from Brune's model of dislocation[4]. That is, the measured spectra are comparatively flat for the long period range with a corner frequency, at which the spectra begin falling off. In the present paper, the measured spectra are used for comparison of source parameters of all the earthquakes based on a simple scheme for comparing source parameters that result from Brune's model of dislocation as derived by Hanks and Thatcher[6].

(3–2) Brune's model of dislocation and an $\Omega - f_c$ diagram proposed by Hanks and Thatcher

Brune has proposed a simple dislocation model of earthquake source to derive near and far field spectra for shear wave and suggested that comparison of observed and theoretical spectra could be used for estimating the effective stress, stress drop and the rupture dimension of earthquake[5]. According to Brune's model, the source radius of earthquake, r, approximated by radius of equivalent circular dislocation surface is related to the far field shear displacement spectral corner frequency f_c by

$$r = 2.34\beta / 2\pi f_c \qquad (1).$$

The stress drop $\Delta\sigma$ that is equal to the effective stress σ_{eff} for total stress drop is given by

$$\Delta\sigma = 7M_0/16r^3 \qquad (2),$$

where M_0 is seismic moment. The seismic moment is related to the long period shear displacement spectral level Ω through the result of Keilis-Borok[10],

$$M_0 = 4\pi\rho\beta^3\Omega R/R_{\theta\varphi} \qquad (3),$$

where ρ is the density, R is a reference hypocentral distance, and $R_{\theta\varphi}$ denotes radiation pattern. Hanks and Thatcher have developed a simple scheme for representing source parameters in terms of the three independent spectral parameters that specify the far field shear displacement spectra that result from Brune's model described above[6]. Using (1), (2) and (3), they obtained the following relation for the total stress drop model,

$$\sigma_{eff} = \Delta\sigma = 106\rho R\Omega f_c^3/R_{\theta\varphi} \qquad (4).$$

As is easily found from this equation, equi-stress-drop is expressed by a straight line in a diagram of log-log plot of Ω versus f_c which is termed an $\Omega - f_c$ diagram by Hanks and Thatcher. The $\Omega - f_c$ diagram is convenient for comparison of source parameters of many earthquakes.

(3–3) Results: Comparison of source parameters

Fig. 8 compares the spectral parameters of the nine earthquakes listed in Table I by use of the $\Omega - f_c$ diagram. Since the spectra were determined on only one component in this study, all spectral amplitudes were multiplied by $\sqrt{2}$. The corner frequencies as well as the long period spectral levels are difficult to be definitely determined from the spectra shown in Fig. 7. Thus, the possible ranges of the values of the spectral parameters are shown by lines in this figure. The earthquake numbers are indicated beside the $\Omega - f_c$ points. The earthquake numbers are the same as those in Fig. 1. The solid lines are lines of constant stress drop with the value indicated. In this diagram, the numbers of aftershocks (N) are symbolically shown as follows: ○; $N \leqq 10$, ◑; $10 < N \leqq 20$ and ●; $N > 20$.

It is difficult to obtain reliable values of source parameters for the earthquakes treated here, since the spectral parameters cannot be fixed uniquely from Fig. 7. Nevertheless, comparison of the relative values of the source parameters obtained can be considered as meaningful. This paper mainly concerns a comparison of the source parameters of the earthquakes examined. Fig. 8, with reference to Fig. 1, indicates generally that the earthquakes occurring in the northern and middle parts of the seismic zone have larger stress drops and smaller dimensions than those in the southern part and Wachi-cho region. It is found that, for the earthquakes of similar magnitude, the stress drop differs with regions by an order of magnitude or greater. Fig. 8 also indicates that the stress drops of the earthquakes following a large number of aftershocks are generally smaller than earthquakes with low aftershock activity. The aftershock activity of the seismic zone concerned was examined in detail by Okano[1]. The regional variation of aftershock activity indicated by the number of aftershocks is reproduced from his paper in Fig. 9. This figure shows that the aftershock activity in the northern part is lower than that in the southern part and Wachi-cho region. It is noted that the regionality of source characteristics is very similar to that of aftershock activity.

The rupture dimensions $2r$ estimated from eq. (1) are shown in Fig. 8. For the largest of the earthquakes examined in the present paper, the Wachi-cho Earthquake, the rupture dimension is estimated to be about 6 to 8 km. This value agrees fairly well with the aftershock area observed imediately after the main shock occurrence in August 18, 1968[13]. The Miyama-cho Earthquake, which is the second largest, is estimated from Fig. 8 to have very small source size (1 km or less). The aftershock activity of this event is unusually low for an earthquake of magnitude 5.4. As is stated above, only fourteen aftershocks of magnitude 1.5 or greater were observed within a month after the main shock occurrence according to the routine observation.

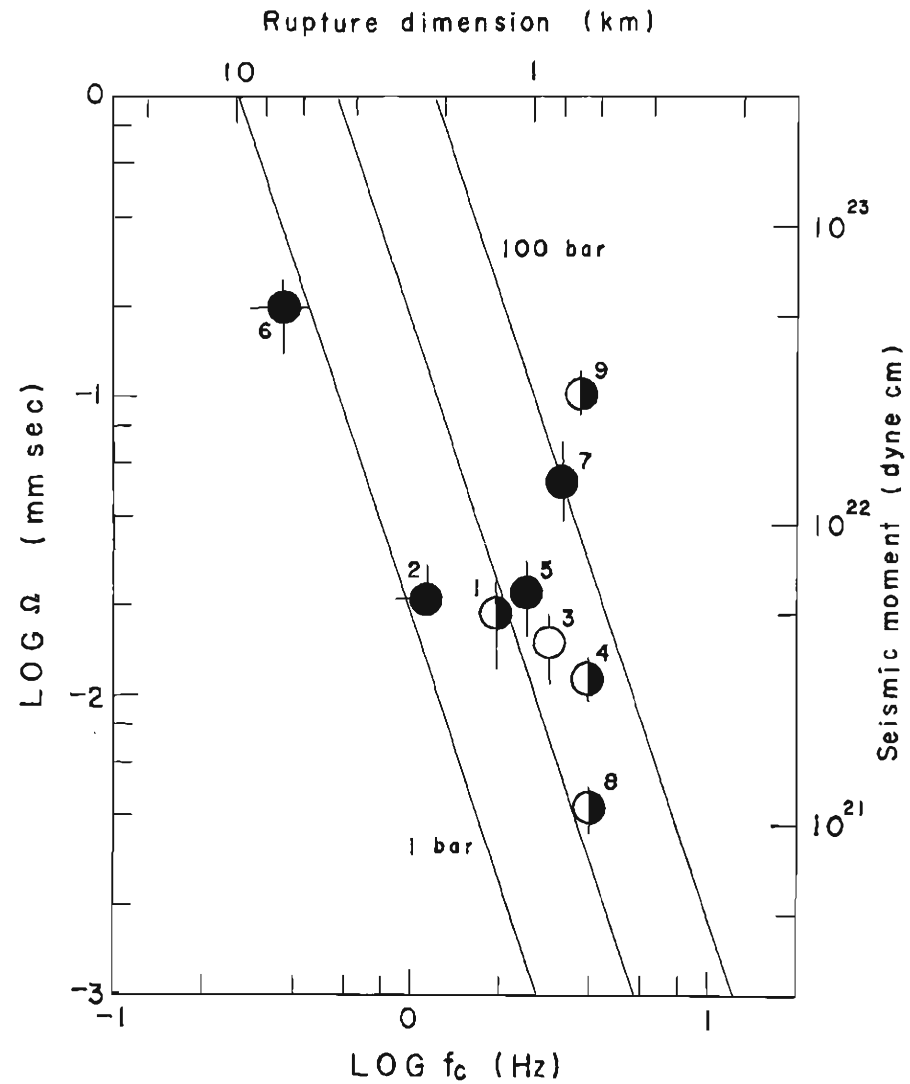

Fig. 8. Ω-f_c diagram for representing spectral parameters of the earthquakes listed in Table I.

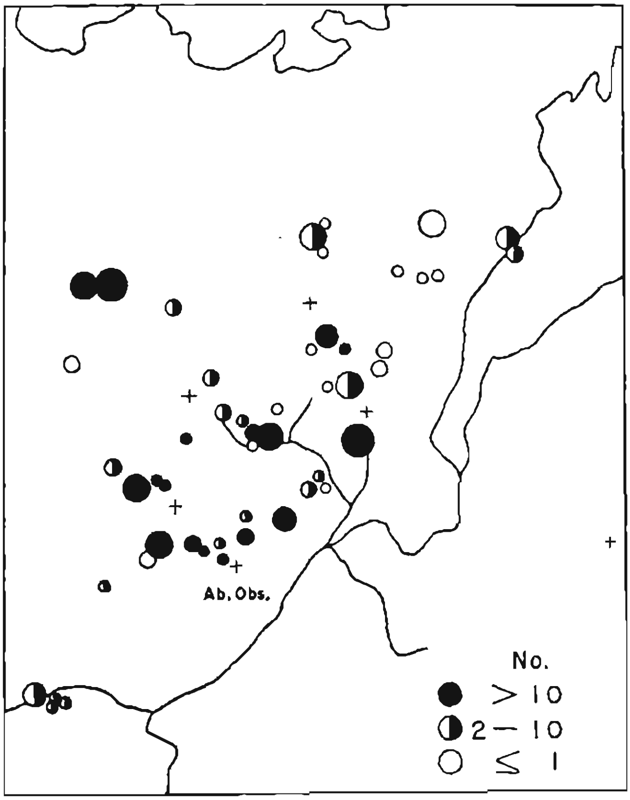

Fig. 9. Regional variation of aftershock activity indicated by the number of aftershocks (N) after Okano[1].

These aftershocks are distributed within an area of about ($2\,\text{km}\times 5\,\text{km}$) or less according to the data from the routine observation. It is noted that, so far as the earthquakes examined in the present paper are concerned, the aftershock areas, if estimated from the area where aftershocks of magnitude of 1.5 or greater occurred, are not too dependent on magnitudes but closely related to the source regions.

Approximate seismic moments of the earthquakes treated here could be determined by use of Fig. 8. The values of seismic moment based on the data of the present study are generally small compared with those derived from the relations between seismic moment and earthquake magnitude which have been obtained hitherto by several authors.

There is no great difference in focal depths of earthquakes examined in the present paper. It is, thus, difficult to find any significant correlation between source characteristics and focal depths. The earthquakes No. 2 and No. 9 have nearly the same focal depths. The source parameters are, however, quite different from each other. The earthquakes No. 1, No. 3 and No. 8 with comparable magnitudes have nearly the same focal depths. However, the spectral parameters of these earthquakes are different respectively. The difference of the source characteristics for the earthquakes examined seems to be related more closely to the source regions rather than to focal depths. However, a general conclusion cannot be drawn concerning the relation of the difference of source characteristics to focal depth for lack of useful data in the present study.

4. Summary and discussion

A comparison of source parameters of earthquakes of magnitude of 4.5 or greater in the seismically active zone in the vicinity of Kyoto illustrates a striking contrast in the source characteristics between the northern and southern parts of the seismic zone. The northern sources are, in general, characterized by high stress drop and small source dimension, whereas the southern sources are characterized by low stress drop and large dimension. Earthquakes with source in the middle part have intermediate values of source parameters between the northern and southern sources. The source characteristics seem to vary gradually from south to north except for Wachi-cho region. Wachi earthquakes have nearly the same characteristics as southern sources. The above regionality of source characteristics is very similar to the regional variation of aftershock activity in the seismic zone concerned. The data examined in the present paper, if compared with the regional variation of aftershock activity[1)], indicate that earthquakes accompanied by the higher aftershock activity have generally the smaller stress drop. As has been already reported[2)], the regional variation between the northern and southern parts also exists in seismic wave attenuation. Attenuation in the seismic zone concerned is, as a whole, small for seismic waves propagating in the EW direction which coincides with the direction of the global tectonic force. Seismic wave attenuation in the northern part is, however, small compared with that in the southern part.

A possible interpretation of the high stress drop and the smaller dimension of earthquakes in the northern part compared with the southern part and Wachi region may be that higher effective stress is acting in the northern part. The low seismic wave attenuation and the small aftershock area in the northern part compared with the southern part seem to support this interpretation. Furthermore, from all the above observations, it is not too unreasonable to speculate that strain in the southern part is apt to be released at a comparatively low stressed stage compared with that in the northern part. The routine microearthquake observation which has been carried out since 1963 shows that, in the southern part of the seismic zone, earthquake swarms often occur and small earthquakes of magnitude less than 3.0 often accompany a large number of aftershocks[12)]. In contrast, in the northern part, aftershock activity is generally low and earthquake swarms seldom occur. The largest two destructive earthquakes occurring in the seismic zone concerned in history (the 1185 Earthquake $M7.6$ and the 1162 Earthquake $M7.3$) have been estimated to have their origin in the west coastal region of Lake Biwa near the north end of the seismic zone[13)]. These earthquakes might be caused by a sudden release of ultimately highly concentrated stress in the northern part. Such a great earthquake, if the above speculation is accepted, might be rather difficult to occur in the sothern part because stress might be released there before it became highly concentrated.

Acknowledgments

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References

1) Okano, K.: Aftershock Activity in the Vicinity of Kyoto, Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 20, 1970, pp. 17–22.
2) Okano, K. and I. Hirano: Seismic Attenuation in Relation to the Tectonic Force in the Vicinity of Kyoto, Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 22, 1973, pp. 97–110.
3) Okano, K.; I. Hirano and A. Kuroiso: Seismic Activity in the Vicinity of Kyoto for These Ten Years (1964–1973), Rep. Coord. Commit. Earthq. Prediction, Min. Constr., Vol. 11, 1974, pp. 109–111 (in Japanese).
4) Brune, J. N.: Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes, J. Geophys. Res., Vol. 75, 1970, pp. 4997–5009.
5) Brune, J. N.: Correction, J. Geophys. Res., Vol. 76, 1971, p. 5002.
6) Hanks, C. N. and W. Thatcher: A Graphical Representation of Seismic Source Parameters, J. Geophys. Res., Vol. 77, 1973, pp. 4393–4405.
7) Okano, K. and I. Hirano: Recent Seismic Activity in the Vicinity of Kyoto — The Earthquake Swarm Occurring in Wachi-cho Region, Rep. Coord. Commit. Earthq. Prediction, Min. Constr., Vol. 5, 1971, pp. 46–48 (in Japanese).
8) Okano, K. and I. Hirano: Seismic Wave Attenuation in the Vicinity of Kyoto, Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 21, 1971, pp. 99–108.
9) Okano, K. and I. Hirano: Micro-earthquakes Occurring in the Vicinity of Kyoto (II), Spec. Contrib. Geophys. Inst., Kyoto Univ., No. 5, 1965, pp. 151–168.
10) Keilis-Borok, V. I.: Investigation of the Mechanism of Earthquakes, Trudy Inst. Geofis. Akad. Nauk., SSSR, No. 40, 1957 (in Russian), English Transl., Soviet Res. Geophys. Ser., Vol. 4, 1960.
11) Watanabe, H. and A. Kuroiso: Seismic Activity in the Northern Part of the Kinki District and Related Problems (I) — Earthquake Swarm Accompanying the Wachi Earthquake of August 18, 1968, Spec. Contrib. Geophys. Inst., Kyoto Univ., No. 9, 1969, pp. 123–136.
12) Okano, K. and M. Nakamura: The Small Earthquakes Accompanied by Aftershocks, Zisin, II, Vol. 20, 1967, pp. 98–105 (in Japanese).
13) eg. Science Table (Rika Nenpyo) compiled by Tokyo Astronomical Observatory.